VARIABILITY IN SEA SURFACE HEIGHT: A QUALITATIVE MEASURE FOR THE MERIDIONAL OVERTURNING IN THE NORTH ATLANTIC

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ABSTRACT

Sea surface height (SSH) from altimeter observations from 1992 on and from modeling results is investigated to determine the modes of variability and the linkages to the state of oceanic circulation in the North Atlantic. First the altimeter and model simulated SSH are analyzed using the empirical orthogonal function (EOF) analysis. They are found to share a similar leading mode where the center of action is along the Gulf Stream and North Atlantic Current with opposite sign anomalies in the subpolar gyre and in the slope waters along the Eastern Seaboard. The time series of the leading EOF mode from the altimeter data shows that between winters of 1995 and 1996, SSH over the Gulf Stream decreased by about 12cm which change is reproduced by the model simulation. Based on the relationship from the model simulations between the time series of the SSH EOF1 and meridional heat transport, it is suggested that associated with this SSH change in 1995-96, the overturning has slowed down from its heights in the early 90's. Furthermore, it is shown that decadal variability in the leading SSH mode originates from the thermal forcing component. This adds confidence to the qualitative relationship between the state of overturning/ meridional heat transport and SSH in the limited area described by the EOF1. SSH variability in the eastern side of the North Atlantic basin, outside the western boundary current region, is determined by local and remote (Rossby waves) wind stress curl forcing.

1. INTRODUCTION

Decadal variability in the sea surface temperatures (SST) (Deser and Blackmon, 1993) and in the subsurface temperatures (Levitus, 1989; Molinari et al. 1998; Curry et al. 1998) in the North Atlantic inspire thoughts as to whether any of this variability could be linked to the changes in oceanic circulation and especially in the meridional circulation cell. The SST time series extend back to the mid 1800's and limited subsurface observations are available since the 1960's, but neither of them provide an integrated picture of the upper ocean above the permanent thermocline which is anticipated to partake in the thermohaline circulation. Thus, one wishes to find a simple measure to describe at least qualitatively the state of overturning. Since one would expect overturning changes to be associated with heat content changes, sea surface height would be an ideal candidate to reflect overturning changes. Such information may be contained in tide gauge records from around the North Atlantic Ocean, many of which cover over 70 years. The tide gauge data is known to contain considerable power at a quasi-decadal periodicity (about 12 years) especially along the US East Coast (Maul and Hanson, 1991; Unal and Ghil, 1995). However, the interpretation of this low-frequency variability seen in the coastal data is difficult without information on the open ocean sea level variations which we expect to determine the variability at the coast. The satellite altimeters (Geosat (1985-1988) and TOPEX/Poseidon (1992-) have enabled extending the measurements of variability to the open ocean with accuracy within a few centimeters (Mitchum, 1994). SSH only from the latter instruments are used.

The sea level variations excluding tides can be divided into three categories: a) barotropic response to the wind stress field, b) changes due to heating and cooling and c) internal fluctuations of the density surfaces due to a dynamical process such as (baroclinic) Rossby wave passage or Ekman pumping (up/downwelling). The last topic has been explored by Sturges and Hong (1995) who investigated Bermuda sea level variations. They find that an integration of a linearized vorticity equation for the first vertical mode using wind stress curl derived from Comprehensive Ocean Atmosphere Data Set (COADS) gives an excellent fit at

low-frequencies with the observed Bermuda sea level. Addition of higher modes did not improve results, but degraded the agreement. The reason for this may lie in the sensitivity of the vertical mode decomposition to the topography. The spectrum of the Bermuda sea level computed by Sturges and Hong is red for frequencies down to (1/512 months) but the power may actually decrease for even lower frequencies. While Sturges and Hong considered only Bermuda sea level, Frankignoul et al. (1997) show based on model results that the red noise response in sea level in subtropics is expected with power increasing quadratically in respect to the distance from the eastern boundary.

The behavior of sea level along the US coast and at Bermuda is in an apparent contradiction with each other since the coastal tide gauge data shows significant power at decadal frequency and the open ocean data lacks it. This issue is explored here using model generated sea surface height data for period 1951-1993. The model and its forcing, monthly COADS anomalies (daSilva et al. 1994) added to a monthly climatology, are the same as discussed in Häkkinen (1999). Additional model experiments are performed using the same forcing data but removing either the wind stress anomalies or thermal forcing anomalies. The objective here is to investigate to what degree the thermal forcing and wind forcing determine the sea level variability and in what regions their influence is concentrated. In Häkkinen (1999) it was shown that SSH variations along the Gulf Stream were linked to meridional overturning changes. Here it will be shown that indeed the thermohaline forcing dominates the SSH in the Gulf Stream -North Atlantic Current area, in the subpolar gyre and in the slope waters along the US East coast. A comparison with the coastal sea level will not be done as it may not be meaningful because the ocean model has a coarse resolution with topography often lacking in the shelf area.

Altimeter (TOPEX) data is investigated to explore the present status of the meridional overturning. Furthermore, the altimeter data is compared to the model simulation using NCEP Reanalysis data (from 1958-1997) to force the model. With the model results as guidance the variations in the short altimeter record can be put into a long term perspective. As it is known

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there was a reversal in the North Atlantic Oscillation (NAO) index in 1996, this study aims to elucidate the implications of this event. Since the previous model results indicate NAO related oceanic heat flux to be crucial in determining the state of overturning in the North Atlantic, it is of great interest to find whether such a shift is present in the data.

Contents are organized such that in Section 2, a brief description is offered on the model and model experiments which are designed to differentiate between the thermal and wind stress forcing derived influence on SSH. In Section 3, the numerical experiments and altimeter data are analyzed, and comparisons are made to the meridional heat transport variations. Finally the relationship between SSH, upper ocean heat content and gyre circulation is explored in Sections 4 and 5.

2. MODEL EXPERIMENTS

Since this model is published earlier, the reader is referred to Häkkinen (1999) for details of the numerical model which covers both the Arctic and the North Atlantic with the southern boundary at 16S. The resolution is 0.7degx0.9deg and there are 20 sigma-coordinate levels. The model experiments are designed so that the forcing by wind stress curl anomalies and thermal forcing anomalies are applied separately and compared to the model experiment which contain the both components. Total separation of the oceanic response cannot be achieved because the wind and thermally driven dynamics interact, but one hopes to identify regions of the strongest influence by wind and thermal forcing. These regions may be overlapping but also the temporal behavior can be used to distinguish the dominant source of forcing. Four model experiments will be discussed in which the basic monthly climatological surface forcing is altered by adding the following anomalies:

(1) anomalies in wind and thermal forcing (E1) (Häkkinen, 1999),

(2) anomalies in thermal forcing only (E2) (wind stress forcing follows monthly climatology)

(3) anomalies in wind stress forcing only (E3) (thermal forcing contains monthly climatological wind speed and air temperatures etc.). The anomalies in E1-E3 are from COADS data base

(daSilva et al. 1994). Simulation period is 1946-1993, but only period 1951-1993 are used for analysis as in Häkkinen (1999).

(4) anomalies in wind and thermal forcing from NCEP/NCAR Reanalysis (E4) for the period 1958-1997, with the initialization from the experiment E1 as of December 31, 1957.

3. ANALYSIS OF ALTIMETER AND SIMULATED SSH

3.1 The leading modes of variability

To determine the regions with the highest variance in SSH, EOF analysis is performed on the detrended SSH anomalies from each experiment. The variance explained by the first EOF mode is 13.4% in E1, 27.7% in E2, 9.3% in E3 and 12.8% in E4. In the case of the second EOF mode, the variances explained are 8.1%, 10.9%, 7.% and 8.8%. The EOFs of SSH in all four cases give a leading mode which has a large amplitude, elongated center along the Gulf Stream and North Atlantic Current with a weaker anomaly extending from the Labrador Sea along the Eastern seaboard of opposite sign (Figure 1a-d; for E1-E4). The prominent center of variability in the Gulf Stream area may result from the changes in the Gulf Stream position, changes in the current speeds (leading to anomalous transport) or transport of warmer waters (anomalous heat content) or from all of them. The model suggests that anomalous currents play a dominant role and will be discussed in Section 5. Overall, the similarity of the patterns between E1 through E4 is not really surprising, after all both the thermohaline and Sverdrup circulation influence the western boundary current region. However, there are slight differences in the east-west location and the northernmost position of the elongated center. The inclusion of both thermal and wind forcing components, in E1 and E4, emphasizes more the out-of-phase variability between the Gulf Stream and the slope water/subpolar gyre anomalies than in E2 and E3. E4 has a second mode (Fig. 2h) which resembles in some respect Figs. 1a-c with a center aligned along the zero line of Fig 1d, but for most part it lacks the bipolar nature (at the mid to high latitudes) of Figs. 1a-c. Also E1-E3 have a second mode (Figs. 1e-g) that captures some features of Fig 1d for E4. In Häkkinen

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(2000) it is shown that at least the first two EOFs for the upper ocean heat content (1000 m in that case) organize themselves as a propagating mode which means that their time series are correlated at lag. When considering the heat content variability (Section 4) it becomes more obvious why the SSH modes should contain some propagating effects, but they may not be completely distinguishable from noise in SSH as will be discussed below. Thus, spatial patterns of the EOFs have some sensitivity to which part they prefer to capture from the propagating nature of the SSH variability.

The principal coefficient (PC) (i.e. temporal coefficient) of the leading spatial pattern is depicted in Fig. 2a-d for E1-E4. The differences in the time evolution indicate that the thermal forcing imposes more pronounced decadal low-frequency component than wind forcing. The cross-correlation for 516 months between PC1 of E1 and E2 is 0.84 while between E1 and E3 it is -0.34. The former correlation is significant at 95% level considering that the autocorrelation period of 3 years (Fig. 3) reduces the degrees of freedom to 12, but the latter correlation between E1 and E3 does not carry any significance. PC1 of SSH in experiment E3 contains low-frequency variability because the baroclinic adjustment time for remote forcing is nearly a decade but it has no relation to the low-frequency variability of E1 and E2. The underlying quadratic shape over the whole PC time series has surprisingly an opposite curvature between the simulations including thermal forcing anomalies and the simulation with wind stress only anomalies. This very low-frequency behavior is apparent in the NAO index from 1950's to 1990's measuring the strength of the mid-latitude westerlies which were the weakest in the end of 1960's (Hurrell, 1995). Thus, in E1 and E2 cases the quadratic trend can be explained by the weakening of the subpolar heat fluxes which influence the overturning. The quadratic trend of an opposite sign in E3 requires further consideration: Ekman pumping in the 1960's is the weaker than average which can be associated with a weaker than average the subtropical gyre. A weak gyre on the other hand provides less heat to the subpolar gyre leading to a slightly more efficient overturning than in the case of a strong gyre and thus enhancing the boundary current heat content and SSH.

The autocorrelation function of the SSH PC1 can be used to determine whether any cyclic behavior is present. The autocorrelation of the annual average SSH PC1 values is shown in Fig.3 from each experiment after removing the quadratic trend. Considering the autocorrelation time of 3 years, a conservative estimate of significant correlation at 95% confidence level is 0.55 based on 11 (for E4; 12 for E1-E3) degrees of freedom. E1, E2 and E4, all have a minimum at ±6-7 years suggesting a cyclically occurring phenomenon in the SSH variability, while E3 has no indication of such behavior. Although not shown, based on autocorrelation, only SSH PC2 from E2 (thermal forcing anomalies) has an equally strong cyclic variability and is the only one case among the 4 experiments (i.e. in all other cases the second mode, including the one from E4, is indifferent from noise). Also the cross-correlation of PC1 and PC2 in E2 is significant, 0.83 (for annual average values and the quadratic trend removed), with PC2 leading by 2 years. This means that the propagating mode, as manifested by the correlation at a lag and similar cyclicity, is associated with the thermal forcing and thus with the thermohaline circulation. This connection will be discussed further in Section 3.2. The scenario leading to this decadal cyclic behavior due to thermal forcing and associated thermohaline circulation is put forward in Häkkinen (2000).

At present nearly 7 years of altimeter data, May 1992 to December 1998 (in 1x1 degree grid) are available from the NASA Pathfinder project. The leading mode of altimeter SSH shows a concentration of variability in the Gulf Stream area with a time series that has the appearance of much longer term variability than the length of the time series (Figures 4a,b). The EOF1 is very similar to the ones in Fig. 1d attesting to the fact that it is the primary mode of variability with the characteristic out-of-phase relation between the Gulf Stream and the slope waters/subpolar gyre. The most prominent event in the PC1 is the reversal of sign between winters of 1995 and 1996. The change in SSH from winter of 1995 to winter of 1996 at the maximum amplitude of the EOF pattern over the Gulf Stream and the PC is about 12cm both in the altimeter data as well as in the simulation from Figs. 1d and 2d. (The EOF analysis of the simulated SSH data for the period 1991-1997 produces the same EOF1 pattern and

reversal of sign in its time series.) Coinciding with the drop in SSH there was a shift in the NAO index from a positive phase (1995) to a strongly negative phase (1996). Later on it will be shown that the changes in heat content reflected in SSH are not solely driven by local air-sea interaction, although one might anticipate warm heat content anomalies to be associated with the negative phase NAO.

3.2 SSH and meridional heat transport

The model results are used to relate the SSH variability (defined by EOFs) with meridional heat transport which is used as a proxy for overturning. Secondly, meridional heat transport is a simple scalar field compared to numerous choices for defining overturning rate. The meridional heat transport is computed by integrating both vertically and horizontally (west to east) at discrete latitudes (along grid boundaries enveloping a given latitude) the monthly velocity * temperature -flux values. In Fig. 2a-d it is shown that the variations in the SSH model follow within 2 years the anomalous meridional heat transport at 30N. Wind stress forcing anomalies (E1, E3 and E4) give rise to interannual variability through the Ekman and gyre circulation contribution to the meridional heat transport. As seen, experiments E1, E2 and E4 produce a leading SSH mode whose PC is highly correlated with the meridional heat transport. Also PC1 of E3 indicates some resemblance with heat transport because both describe a quadratic trend, but overall the variations in either quantity are modest compared to the variations in E1, E2 and E4. The main conclusion remains that overturning related changes dominate the SSH variability in the Gulf Stream-North Atlantic Current region and in the subpolar gyre and slope waters. Also, a weak amplitude of the SSH EOF1 pattern around Bermuda, leaves Bermuda lacking of the variability related to the overturning compared to the coastal areas.

In Häkkinen (1999) it is shown that the decadal meridional heat transport variability is determined by the leading heat flux mode which is a dipole pattern with opposite sign centers in the subpolar gyre and in the subtropics. This pattern is shown by Cayan (1992) to result from

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variations in the NAO index. This association of the leading heat flux mode underscores the role of NAO in the low frequency variability in quantities related to heat transport and heat content, and thus in SSH (Häkkinen 1999). Based on the SSH PC1 from E4, the shift in 1995-1996 is part of decadal variations dominating the time series (Figure 2d). The meridional heat transport has a very sharp drop after 1994, the negative anomaly is nearly 0.5 PW. This value does contain heat transport changes due to the Ekman transport and wind driven gyre circulation changes and may be an overestimate of the decline in overturning. Nevertheless, it is likely that the TOPEX time series indicates that the meridional overturning is presently in a weak phase.

3.3 Comparison of SSH fields from the different experiments

In the above the relationship between the leading spatial patterns and their temporal variability was studied. But what of the relationship at any given point of the SSH field between the experiments ? How does one reconcile these results showing either the influence of thermal forcing and the observed strong signal at the US East Coast or wind stress curl on SSH and the results of Frankignoul et al. (1997) ? One solution to the dilemma is that the thermally driven and wind stress curl driven SSH changes may occupy mutually exclusive regions. A straightforward computation of cross-correlations can provide further information: The model experiments E1 and E2 give highly correlated sea level variability in areas of mode water formation in the subpolar gyre and subtropics, but E1 and E3 are correlated highly in far more extensive areas of the North Atlantic and especially on the eastern side extending to 60W at the latitude 30N (Figure 5). Thus the Bermuda sea level is mainly affected by the wind stress curl in agreement with Sturges and Hong (1995). The wedge where local Ekman pumping and wind driven Rossby waves contribute the most to the sea level variability has an appearance of a shadow zone of the ventilated thermocline theory. Liu (1993) has shown that local Ekman pumping has to be balanced by Rossby waves in the shadow zone, an anticipated result since the western boundary of the shadow zone is defined by Rossby waves arrested by

the gyre circulation, at least in idealistic layer models. Thus sea level in the eastern basin is determined by wind stress curl which represents a white noise forcing. These two elements enables one to place the conclusions of red noise behavior in sea level by Frankignoul et al. (1997) into perspective. This also means that the Bermuda sea level represents mainly a red noise behavior and is not indicative of overturning variability.

The two methods outlined above are not completely in agreement on the location of the signal related to the thermal forcing: While the EOF analysis points to the western boundary current and coastal region west of it and to the interior of the subpolar gyre, the direct point by point comparison fails to pinpoint most of the Gulf Stream area as a significant common area of variability between E1 and E2. The influence of the wind driven processes clearly imposes a subtle influence to the exact location of the Gulf Stream and the North Atlantic current and their temporal variability which degrades the agreement between E1 and E2 achieved by EOF analysis.

4. SSH AND UPPER OCEAN HEAT CONTENT

At mid-latitudes and in tropics SSH describes variations in heat content of dynamic and/or thermodynamic origin. The heat content in the following is computed for the upper 500 meters which, to a high degree, encompasses the seasonal variations of the mixed layer. To describe how the center of activity in SSH over the Gulf Stream area in terms of heat content originates and evolves, composites are used. In this way one hopes to capture any propagating features that may not be reflected in SSH which contains also barotropic response (increasingly important at higher latitudes). First, all data is binned seasonally (DJF, etc.) and then a quadratic trend is removed. A composite is formed by subtracting heat content fields corresponding to the minima in SSH PC1 from the heat content fields corresponding to the maxima in SSH PC1. The criterion for the extrema in the seasonal SSH PC1 is that its absolute value has to be larger than one standard deviation. Fig. 6a-d shows the heat content evolution simultaneous with the extrema in SSH PC1, and 2 , 4 and 6 years after the

occurrence of the SSH PC1 extrema for experiment E1. Initially at lag 0, as anticipated, the heat content is positive over the Gulf Stream - North Atlantic current region, and negative in the subpolar gyre and along the US coast just as the SSH EOF1 and PC1 jointly describe. During the subsequent years the positive heat content rapidly spreads to the subpolar gyre (years 2 and 4) and starts to exit in the slope waters (years 4 and 6). Year 6 in Fig 6d describes a near reversal of the heat content field at year 0.

The simulated sequence of events in Fig. 6 show that there is a band of heat content anomalies between 20N and 30N representing Rossby waves propagating from the east (Häkkinen, 2000). The heat content anomalies with the same sign continue along the Gulf Stream. Taking into account the reversal of the pattern on year 6, the evolution of the heat content anomalies suggest an organized progression of events: The anomalies over the Gulf Stream are related to the gyre scale changes mediated by Rossby waves and propagate to the subpolar gyre. The completion of the cycle is about 12-14 years as was already indicated by the autocorrelation of the leading SSH mode.

Another significant feature of the composite evolution is the out-of-phase relationship in heat content between the mid-latitudes and tropics when maximum (minimum) heat content/SSH values occupy the Gulf Stream region. Since these events are preceded by intensification (weakening) of the overturning, a simple interpretation is that at least some of the heat transported northward originates from the equatorial region, leaving a cool (warm) anomaly behind. The SSH EOF1 shows this same out-of-phase structure, especially from E4 and from the altimeter data. The in-phase (out-of-phase) variability of the SST at high (mid) latitudes and tropics (i.e. a tripole) in conjunction of a quasi-decadal joint mode with SLP has been found in Tourre et al. (1999). They in fact show that the quasi-decadal mode expands over the whole Atlantic and is likely to involve out-of-phase variations of northern and southern Atlantic Hadley circulation. Also Rajagopalan et al. (1998) suggest the tropical - extratropical linkage to exist between tropical SST and NAO. Thus, there is evidence that the tropics operate in unison with the extratropical North Atlantic at decadal time scales. Based on

the model predicted linkage of SSH PC1 and overturning/meridional heat transport, it is likely that a part of the low-frequency tropical variability is a manifestation of the Atlantic thermohaline circulation variations. One should also note that the tropical anomalies occur only after the maxima (year 0) or minima (year 6) of the overturning as measured by SSH PC1, with no significant anomalies in the intervening years.

The evolution of heat content based on extrema in SSH PC1 for E2 and E4 are similar to E1. In experiment E3 (with wind stress anomalies added to the monthly climatological forcing) the lag 0 picture is similar as it should be. However, no strong propagating signals are found and no reversal of pattern takes place at any lag. Thus, evolution in E3 is significantly different from the experiments which include thermal forcing. This separation emphasizes the role of overturning circulation in determining heat content anomalies in the North Atlantic outside the subpolar gyre in which area thermal forcing is directly influencing water mass formation leading to changes in overturning circulation.

The above sequence of heat content and SSH evolution of Fig. 6 can be applied to the present day North Atlantic: Year 0 represents the situation prevailing 1994- and 1995 and years 2-4 represent years 1997-1998 with negative SSH/heat content over anomaly Gulf Stream and the positive SSH/heat content anomaly in the subpolar gyre. In respect to the changes in the NAO index during this time period the relationship between the subpolar heat content anomaly and the local surface heat flux needs to be considered. After several years of strongly positive index values, the NAO index changed sign in winter of 1996 to a strongly negative phase. Using DJF average value for the NAO index, NAO has been in a weakly negative phase since 1996 until winter of 1999 when positive values dominate again (monthly index values from NOAA/Climate Prediction Center). At the negative phase of NAO the subpolar gyre experiences a heat gain in an anomaly sense (less heat loss than average) and would contribute to warm heat content anomaly. It is significant that the warm anomalies in the subpolar gyre initially derive from subtropics based on the heat content evolution in Fig. 6.

Thus the heat content anomalies in the subpolar gyre are only partly locally forced, and in effect amplified, which would imply the existence of a positive feedback.

5. SSH AND GYRE CIRCULATION

To address the issue why SSH, or equivalently the upper ocean heat content, gives such a strong signal over the Gulf Stream area, connections to the variability in the gyre circulation is searched. The basic hypothesis is that as a result of intensifying wind stress and buoyancy fields, the midlatitudes gyre circulation becomes stronger giving rise to anomalous current transporting more heat northward. To investigate the variability of the horizontal, vertically integrated transport we resort to EOFs which conveniently will separate the buoyancy driven and barotropic wind stress curl driven transport changes in the streamfunction. The average transport streamfunction for 43 years is shown in Fig 7 (shown only for E1, but all other cases are very similar) on which the leading modes of variability in Fig. 8a-d (the first two shown for E1, only the first one for E2-E3) are superimposed on. In E1 and E2 the first mode describes simultaneous intensification or weakening of both the northern recirculation/subpolar gyre as well as that of the subtropical gyre. Since E2 forcing included only the anomalies for thermal forcing, this first mode is related to the variability of the overturning cell. In E1, the second mode describes variability limited to the western half of the basin coupling the subpolar and subtropical regions. This second mode of E1 is the leading mode of E3 where the climatological forcing was appended by anomalies only from wind stress curl, thus wind stress curl driven circulation changes have their own identifiable pattern but it is only of secondary influence compared to the thermal driving.

The times series associated with the variability of the vertically integrated transport is displayed in Fig 9a-c where the PC1 for E1-E3 are shown in low pass filtered and detrended form along with the meriodional heat transport anomaly at 30N. In Fig. 9d PC2 of E1 is shown with the negative of the NAO index (from the NOAA/Climate Prediction

Center), both detrended and low-pass filtered. The similarity of PC1 with SSH PC1 in E1-E2 with Fig. 2a,b is evident but such that SSH PCs lag streamfunction by 1-2 years. Also the simultaneous correlation of the meridional heat transport at 30N and PC1 is very high and statistically significant (for E1 and E2). The lack of correlation between meridional heat transport and PC1 in E3 reconfirms the different source of variability in the first mode of E3. Furthermore, PC2 of E1 and PC1 of E3 have a close resemblance with minor differences in the amplitudes of some of the extrema. Both of the time series (monthly values) are highly correlated (-0.57, -0.59 respectively) with the NAO index at zero lag. Negative correlation means that stronger westerlies induce an anticyclonic circulation anomaly north of 30N where the strongest gradient (i.e. curl) is located. A not as strong strengthening of trades associated with NAO gives a cyclonic anomaly in the subtropics. A similar streamfunction pattern as in Fig.8b and 8d appears also in Greatbatch and Goulding (1989) as the wintertime (for January through March) circulation anomaly as a deviation from annual mean. The similarity should be anticipated since the strength of the wintertime atmospheric circulation is stronger than in the other seasons. Thus we conclude that the second mode of the E1 streamfunction (the first mode of E3) represents the barotropic (Sverdrup) transport variability. Overall, the amplitudes of the buoyancy and wind stress curl driven transport variability are limited to +/- 12Sv (not shown), which are reduced by low-pass filtering (removing periods of less than two years) to +/- 6-8 Sv. Such deviations represents 10-15 % of the mean gyre strength of about 60Sv for the subtropical gyre.

To explore the relationship further between the gyre circulation and heat content anomalies, the time-evolution of seasonal (DJF, MAM, etc) SSH anomalies (SSHA), upper 500 meter heat content and streamfunction values are plotted at 70W from 20N to 40N from experiment E1 in Fig. 10a-c (low pass filter has been used to remove variability less than 2 years and no detrending has been applied). SSHA as expected from its PC1 shows 3 cycles of decadal anomalies which appear to move in from south to the Gulf Stream region but become strongly amplified after 30N. Streamfunction shows

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intensification at the same time as the SSHA amplifies and at the same latitude. From the relationship between the variations in the streamfunction with the SSH PC1 (and with the meridional heat transport at 30N), it is confirmed that anomalies of SSH and heat content are associated with western boundary current strength: Cold anomalies (low SSH) dominate the Gulf Stream region when the gyres are weak, and warm anomalies (high SSH) prevail when the gyres are strong. At the maxima of the subtropical gyre strength (at 70W), there is also movement of the stronger transport values northward as the streamlines get closer together (since the zero-streamline moved hardly at all) which means that actual current speeds have increased at latitudes 32N-36N which would effectively carry warm waters northward. The upper ocean (500m) heat content shows similar quasi-decadal variability as SSHA but the warming (cooling) events precede the high (low) SSHA events by about 2 years (note: the NAO related heat flux is at maximum 1-2 years before the maximum SSH anomaly as discussed in Hakkinen (1999)). A typical heat flux anomaly associated with NAO in this region is +/-50W/m2 which prevails for about 2-3 winters. Within one winter this heat flux would give about 0.2C temperature change in 500 meter water column which is about the magnitude that the isotherms in Fig. 10b meander. This suggests that temperature anomalies themselves would not be dominating the SSH signal, but the current speed changes associated strengthening gyre circulation which conclusion applies to all experiments E1-E3 (and E4).

6. SUMMARY

Sea surface height variability is analyzed from ocean model simulations and from altimeter data. Model experiments with both wind stress anomalies and thermal forcing anomalies and either one excluded are considered. It is found using the empirical orthogonal function (EOF) analysis that they all share the leading mode where the center of action is along the Gulf Stream and North Atlantic Current with opposite anomalies in the subpolar gyre and along the US eastern seaboard. Also, the leading SSH mode shows a significant out-of-phase

relationship between Gulf-Stream area and the tropics and at the same time, an in-phase relationship between subpolar gyre and the tropics, as also found in studies of SST by Tourre et al. (1999). The intercomparison of SSH between the simulations excluding or including thermal forcing or wind stress anomalies suggest that away from the western boundary current region and towards the equator, the SSH variability is to a high degree determined by wind driven processes (local Ekman pumping and wind driven Rossby waves). In the formation areas of subtropical and subpolar mode waters, the SSH variability is determined mainly by thermal forcing.

Longer hindcast runs are used to make the connection between the time series of the SSH EOF1, meridional heat transport and variations in the North Atlantic Oscillation. Thus we can have a qualitative estimate of the state of overturning/ meridional heat transport based on SSH. The time series of the leading mode is dominated by a very low-frequency variability which the model associates with decadal variations in the thermohaline circulation. The model results are interpreted as such that thermohaline circulation variations are manifested in the SSH/heat content in the Gulf Stream area and subpolar gyre. The SSH variability arises from anomalous current speeds rather than anomalous temperatures as the model suggests strengthening gyre circulation at the heights of the SSH anomalies. Besides the extratropical SSH variations, the leading mode of SSH has a signal also in the tropical Atlantic where the tropical decadal variability is well-known from observations (Mehta and Delworth, 1995; Tourre et al. 1999).

The altimeter data suggests that between 1995 and 1996, SSH decreased by about 12cm over the Gulf Stream which is reproduced by the model simulation. Based on the model results, the most significant occurrence coincident with this SSH change in 1995-1996 is the slowing down of overturning as measured by meridional heat transport from its heights in early 90's and which may be as much as 30% of the annual mean. The sheer fact that the model is able to reproduce this abrupt change gives credibility to the model interpretation of the physics related to overturning as the cause. The SSH change between 1995 and 1996 occurred at the

time when the NAO index shifted its phase from positive to strongly negative. Before 1996, the Gulf Stream area contained, according to the EOF analysis, a higher heat content which should have spread around the subpolar gyre in subsequent years as shown by heat content composites based on the model simulation. At the negative phase of NAO, the winter heat loss in the subpolar gyre is weaker than average, i.e. the heat flux anomaly reflects heat gain by the ocean. This means that the heat gain is located in the area with above average heat content (advected from south) which is now enhanced by local heat flux anomaly. This sequence of events suggests that a positive feedback between the atmosphere and ocean may take place in the subpolar gyre as was put forward by Grötzner et al. (1998). Significance of a positive feedback lies in the fact that it is necessary for an existence of a coupled mode. A quasi-decadal scale coupled mode was in fact suggested by Grötzner et al (1998) and Häkkinen (2000) based on the positive feedback and also on existence of mid-latitude Rossby waves as a delayed response.

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FIGURE CAPTIONS:

Figure 1: EOF1 of SSH from E1 (a), E2 (b), E3 (c) and E4 (d). EOF2 of SSH from E1 (e), E2 (f), E3 (g), and E4 (h). Contour interval is 0.2 non-dimensional units.

Figure 2. PC1 of SSH in units [m] (thin solid line and thick dashed line for the low pass filtered form) and low pass filtered meridional heat transport anomaly at 30N in units [PW] (solid thick line) from E1 (a), E2 (b), E3 (c) and E4 (d). The axis for PC1 on right and for meridional heat transport on left.

Figure 3. EOF1 and PC1 of the sea surface height from TOPEX/Poseidon altimeter measurements for period 1992-1998. EOF1 in non-dim. units, interval 0.1. PC1 in units of m. The SSH difference from the 1995 winter to the 1996 winter at the maximum of the spatial pattern (over the Gulf Stream) is 12 cm. The smooth line is 13 month running mean.

Figure 4. The autocorrelation of annual average values of SSH PC1 with a quadratic trend removed. Thick solid line refers to E1, thin solid line to E2, thick dashed line to E3, and thick dash-dot line to E4. An estimate of significant correlation 0.55 (at 95% level) is also drawn based on 11 degrees of freedom.

Figure 5. Month to month , point by point cross correlations of experiments (a) E1 and E2, (b) E1 and E3. Contour interval is 0.1, correlations less than 0.6 are shaded. SSH data was first linearly detrended.

Figure 6. The composite of the upper 500 meter heat content at the extrema of SSH PC1 from experiment E1 where fields corresponding to minima in PC1 (defined by one std) are subtracted from fields corresponding to maxima in PC1. (a) at lag 0, (b) at lag 2 years, (c) at lag 4 years and (d) at lag 6 years after the extrema in PC1. All data are seasonally binned and a quadratic trend has been removed to emphasize the decadal variations. The contour interval is 0.2 C, and dashed shading implies that the temperature difference is significant at 95% level.

Figure 7. The 43 year average vertically integrated transport streamfunction. Negative contours (thin lines) denote anticyclonic circulation and positive contours (thick lines) denote cyclonic circulation. The contour interval is 10 Sv.

Figure 8. Streamfunction EOF1 and EOF2 from E1 (a)-(b); the variances explained are 18.7% and 14.6%. Streamfunction EOF1 from E2 (variance explained 42.2%) (c) and E3 (variance explained 19.9%) (d). Contour interval is 0.2 in non-dimensional units. Negative (positive) streamfunction values denote anticyclonic (cyclonic) circulation.

Figure 9. Streamfunction PC1 (dotted; axis on right; units in Sv) and meridional heat transport at 30N (solid; axis on left; in PW) from E1 (a), E2 (b) and E3 (c). Streamfunction PC2 (dotted; axis on right; units in Sv) from E1 and the negative of the NAO index (solid; axis on left; non-dim.) (d). All quantities are linearly detrended and low-pass filtered to remove variability under 2 years.

Figure 10. The time evolution (from experiment E1) of SSH anomalies (in cm) (a), upper 500 meter heat content (in Celcius) (b) and streamfunction (in Sv) from a cross-section along 70W from 20N to 40N (c). All quantities are low-pass filtered but no detrending has been applied. Contour interval is 2 cm in (a), 0.3Celcius in (b) (only values above 15C shown) and 4Sv in (c).

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

F1

F2

MODE 1

(a)

(b)

YEARS
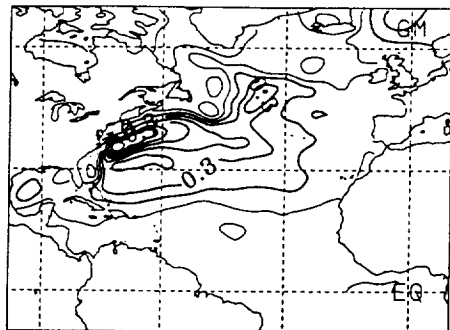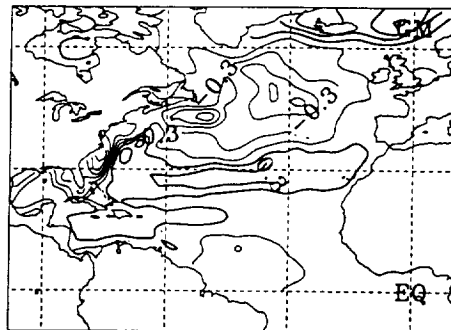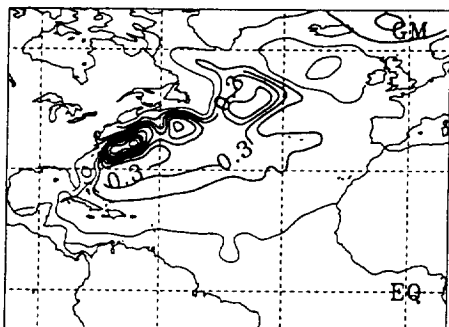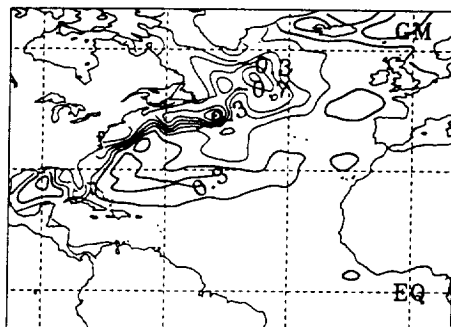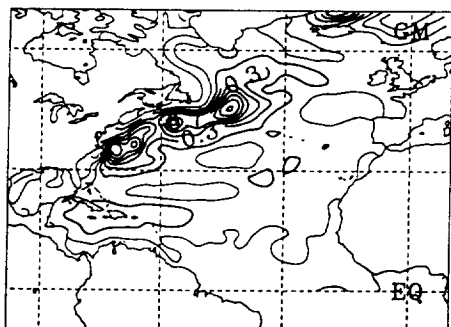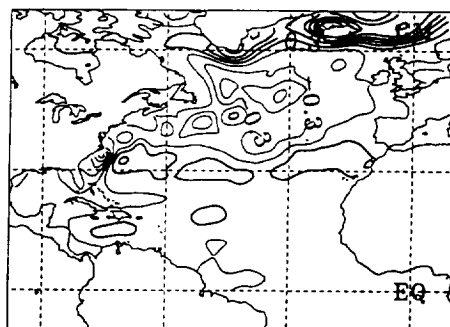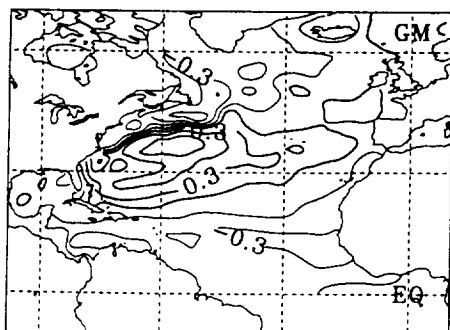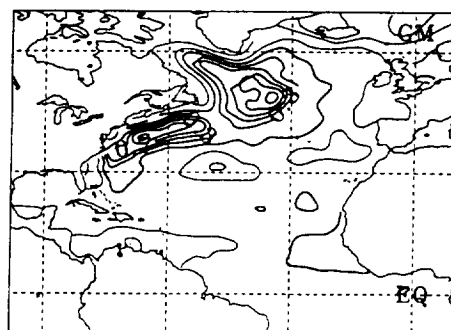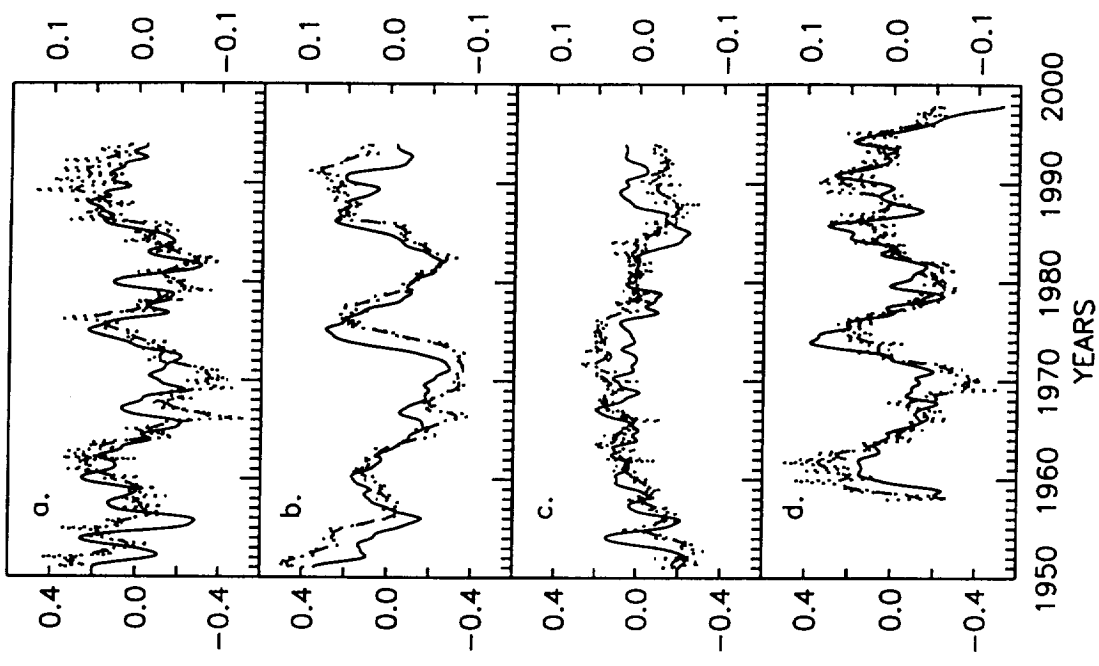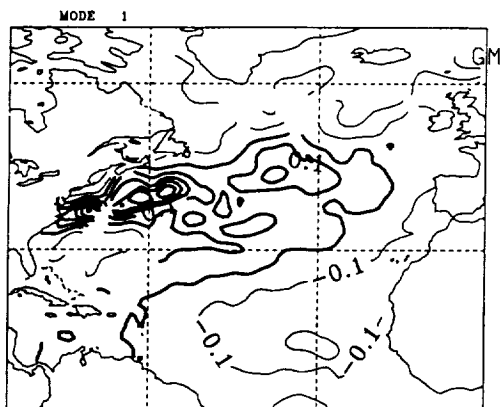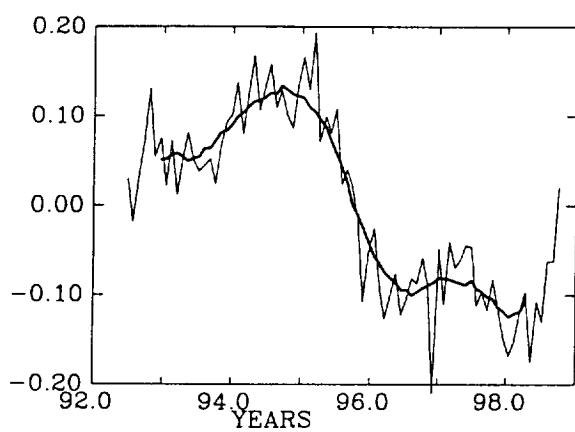
F3

AUTOCORRELATION OF SSH PC1 FOR E1-E4
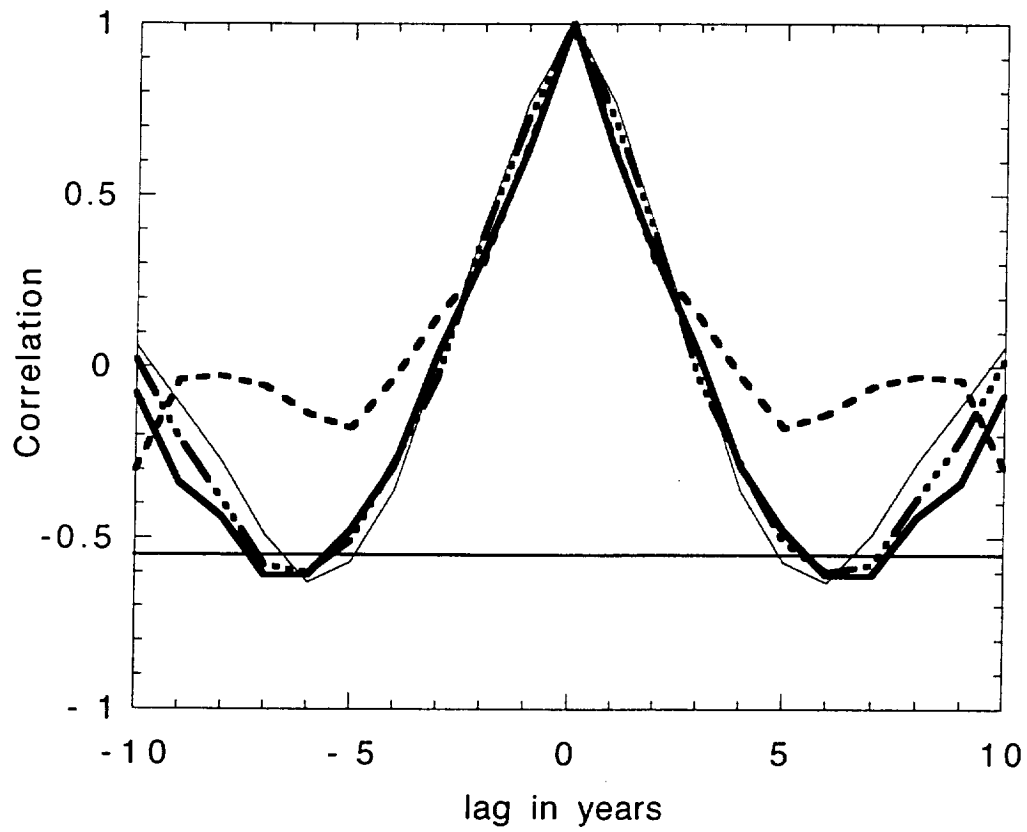
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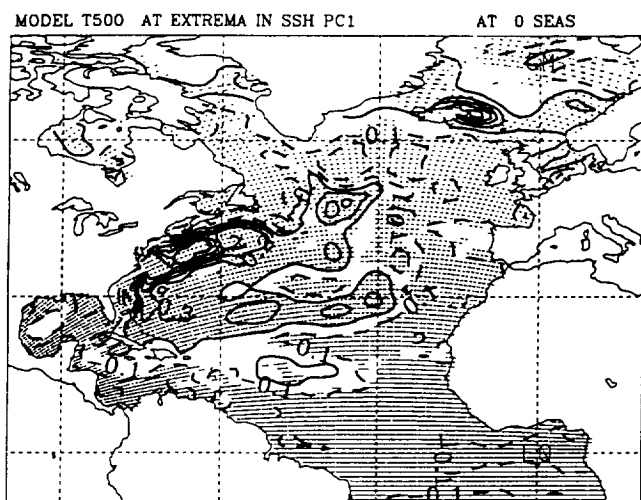/splf5/aux3c3/ssha   /splf5/aux3th/ssha   CORR AT 0 MOS
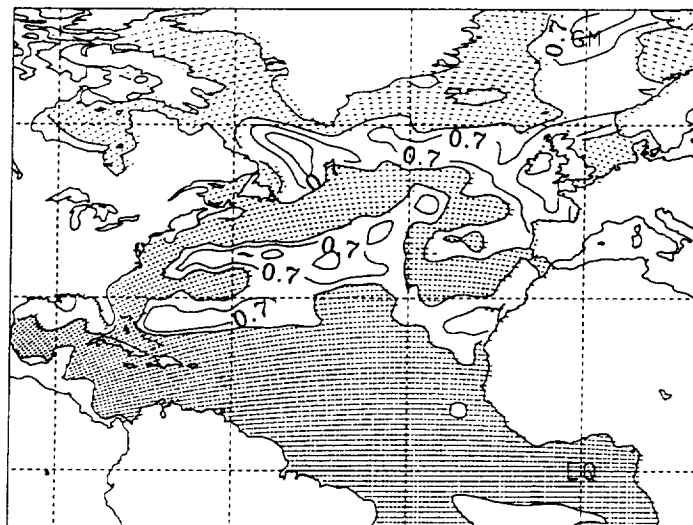
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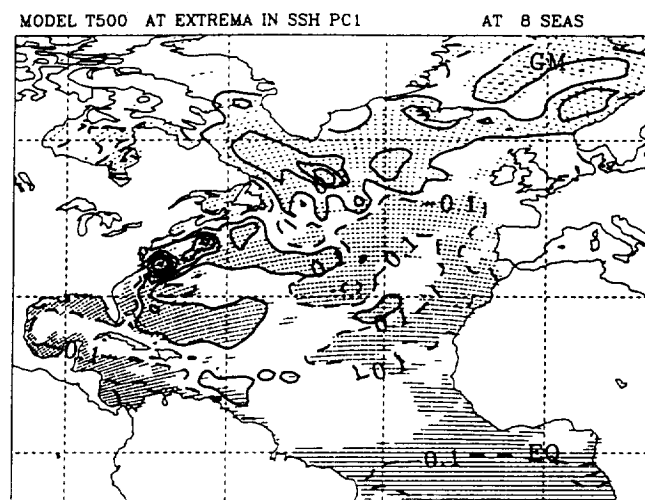/splf5/aux3c3/ssha   /splf5/aux3ww/ssha   CORR AT 0 MOS

(b)

F5
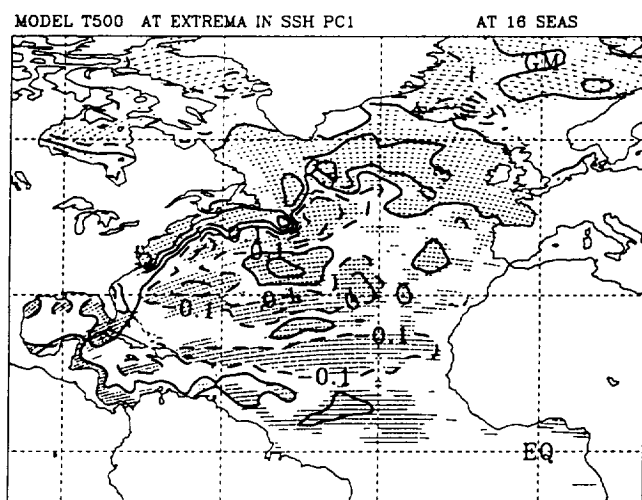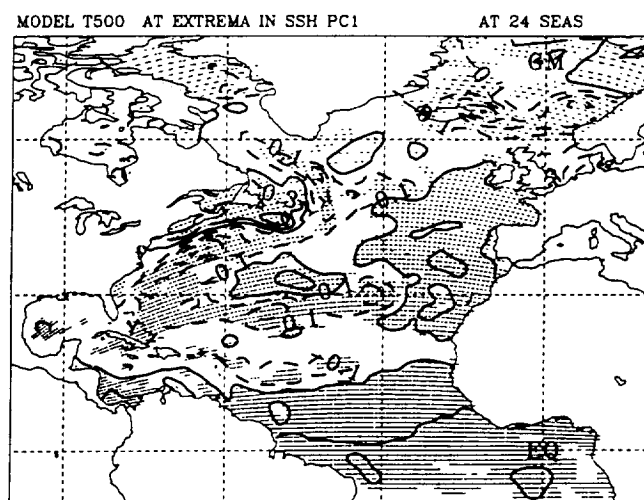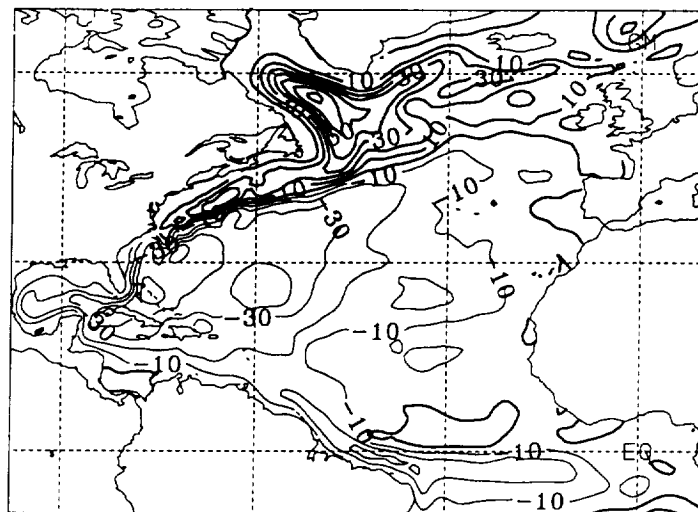
MODEL T500 AT EXTREMA IN SSH PC1   AT 0 SEAS

(a)

MODEL T500 AT EXTREMA IN SSH PC1   AT 8 SEAS

(b)

MODEL T500 AT EXTREMA IN SSH PC1   AT 16 SEAS

(c)

MODEL T500 AT EXTREMA IN SSH PC1   AT 24 SEAS

(d)

F6
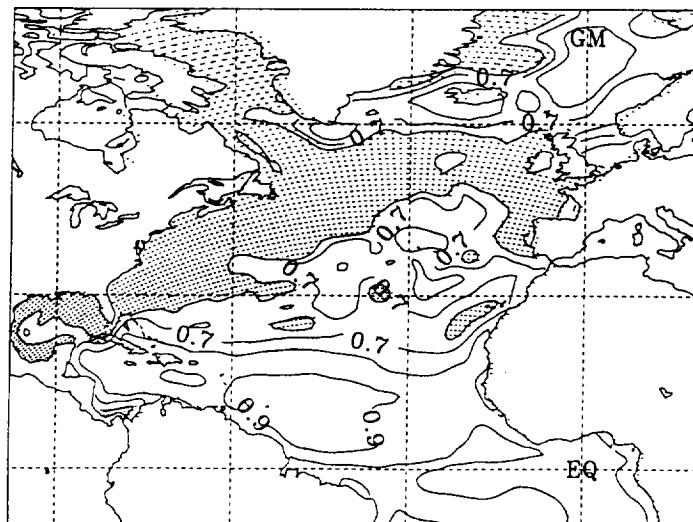
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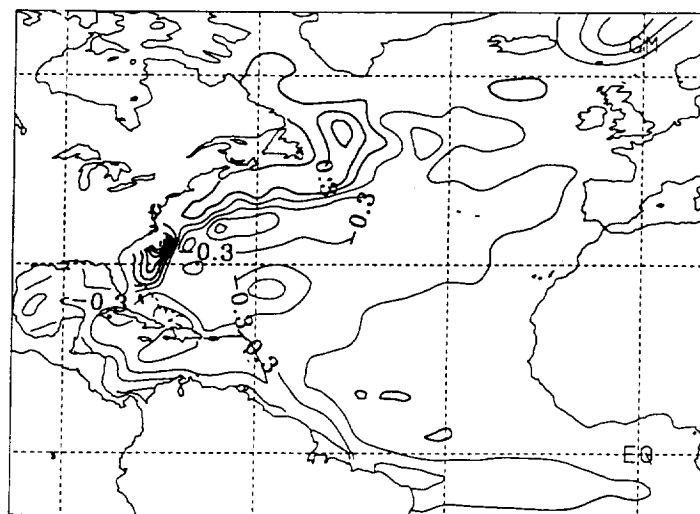
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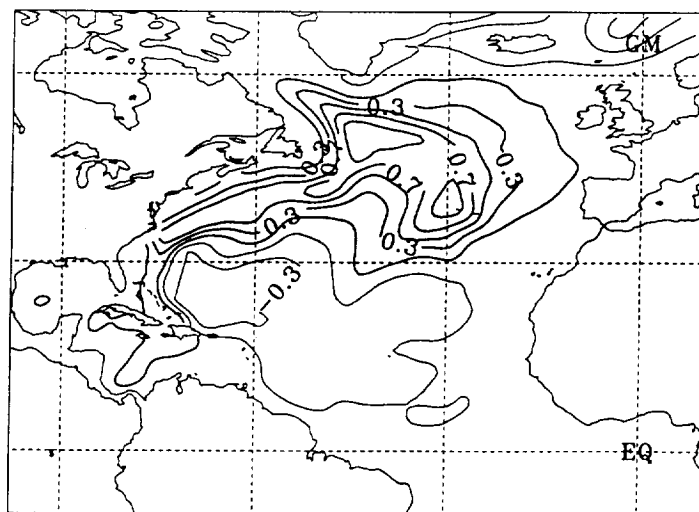
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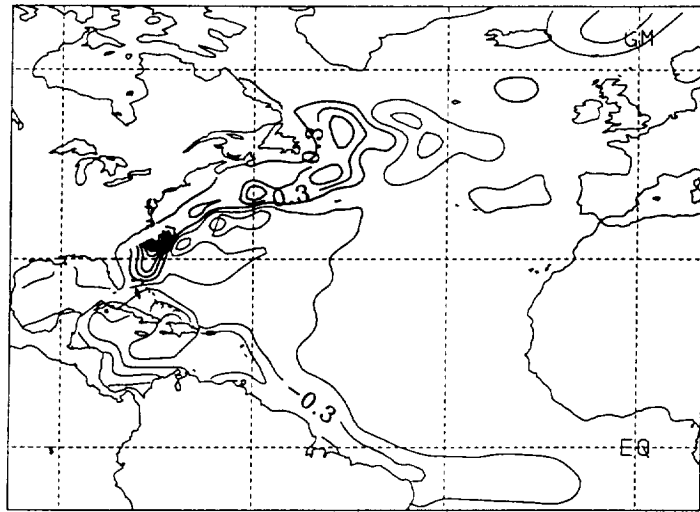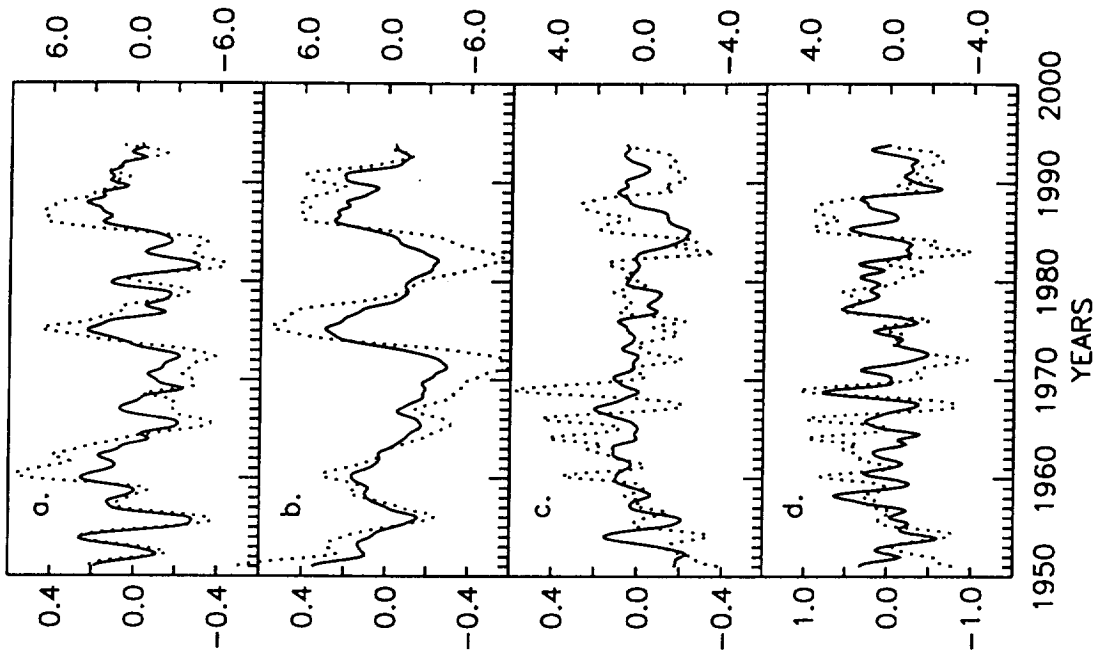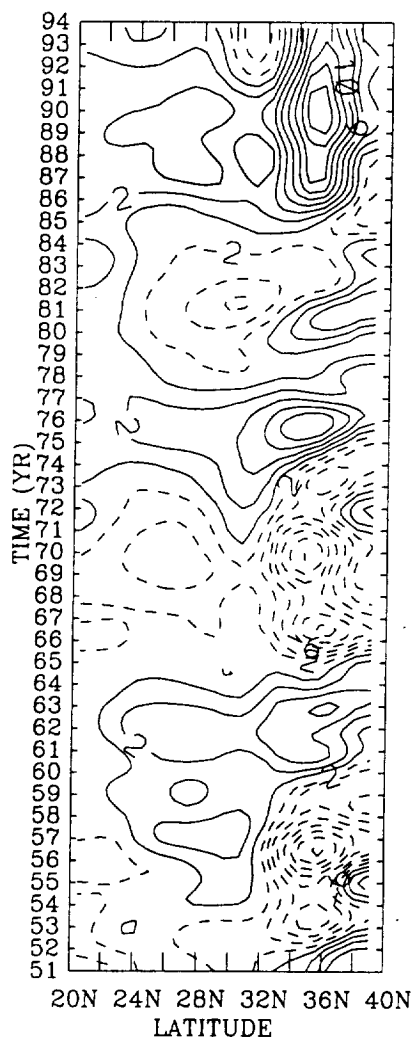
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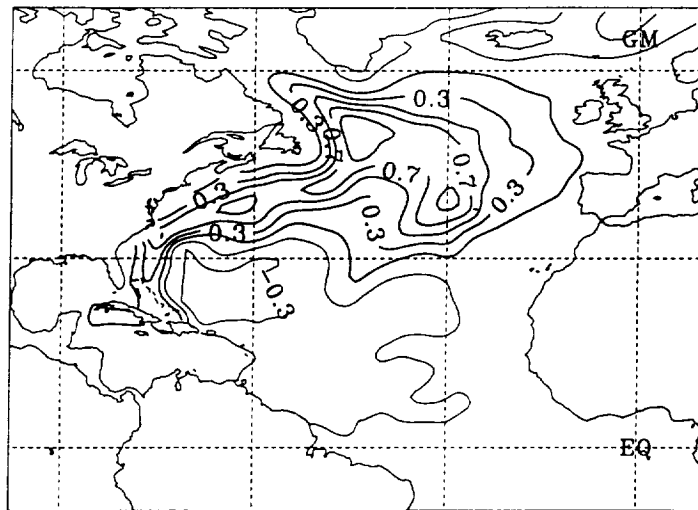
(d)

F8

F9

(a)

SSHA   AT 70W

(b)

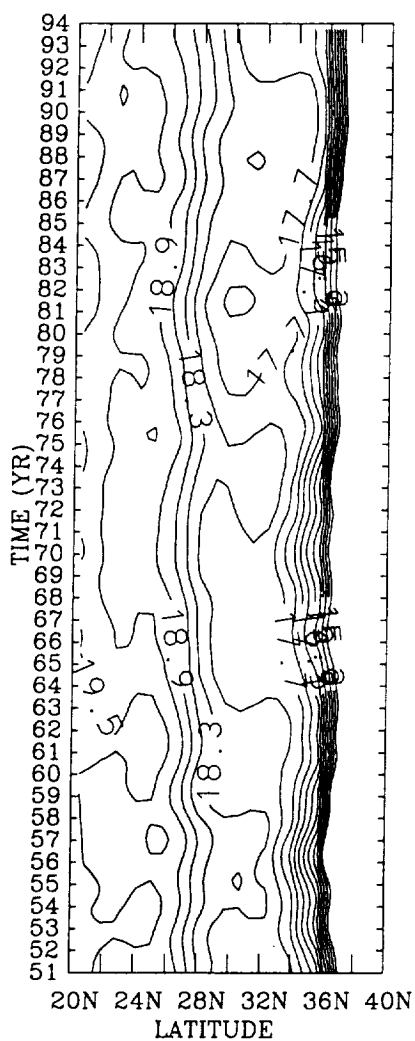T500   AT 70W

(c)

PSI   AT 70W

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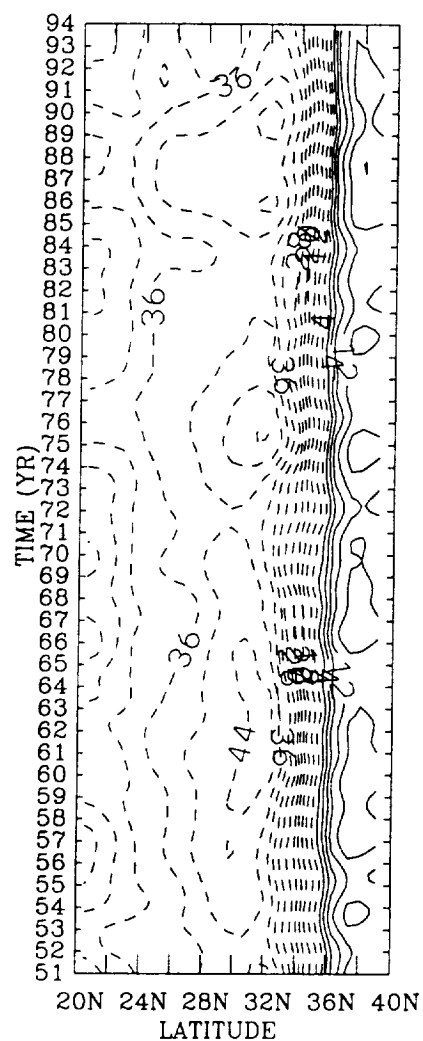
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F10

PAPER SUBMITTED TO J. GEOPHYS. RES. TITLE: VARIABILITY IN SEA SURFACE HEIGHT: A QUALITATIVE MEASURE FOR THE MERIDIONAL OVERTURNING IN THE NORTH ATLANTIC

Sirpa Hkkinen, NASA Goddard Space Flight Center, Code 971, Greenbelt MD 20771

Appropriate Science priority: Long term variability

The paper investigates the short record of altimeter data and uses a 43 year ocean model hindcast to place the variability to a longer term perspective in the North Atlantic Ocean climate. In fact, based on model results the largest signal found in the altimeter data represents slowdown of the meridional thermohaline cell in 1995-1996. Without the model results the interpretation of the significant variation in the altimeter data would not be straightforward.

TITLE: VARIABILITY IN SEA SURFACE HEIGHT: A QUALITATIVE MEASURE FOR THE
MERIDIONAL OVERTURNING IN THE NORTH ATLANTIC

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SIGNIFICANT FINDINGS:

Sea surface height (SSH) from altimeter observations from 1992 on and from modeling results is investigated to determine the modes of variability and the linkages to the state of oceanic circulation in the North Atlantic. The time series of the SSH variability over the Gulf Stream region from the altimeter data shows that between winters of 1995 and 1996, SSH decreased by about 12cm which change is reproduced by the model simulation. This change is attributed to the abrupt change in the North Atlantic Oscillation (NAO) index from positive to negative phase. Long hindcast model runs are used to make the connection between the time series of the spatial variability pattern and meridional heat transport. Based on their relationship from the model simulations, it is suggested that associated with this SSH change in 1995-96, the overturning has slowed down from its heights in the early 90's.